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The adaptability of stilt houses roof structure in earthquake prone region in the context of local seismic culture

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ABSTRACT

Earthquake-prone environmental conditions require the vernacular community in Bima Regency to adapt by carrying out 'innovations' in their stilt houses' structural and construction systems. The bottom structure tends to remain, while the top tends to change. This study aimed to identify the differences in the types of wood joints between the elements and the roof construction on wooden stilts of Mbawa, Maria, Sambori, and Kole Village, Bima Regency, in the context of their adaptability to earthquakes. Case studies through observation and documentation are carried out for data collection and identification processes. The documentation results are then analyzed to ensure the connection type between the elements on each part of the roof truss. Five types of roof truss construction are found, each with some wood connection type: pin, rigid, and friction joint. The integration between joints of the roof truss with the unique construction developed to date has proven to adapt to earthquake-prone environments. The changes made by the community to improve the seismic adaptability of uma panggu show that the local seismic culture is still developing in Bima Regency.

Introduction

Sumbawa Island has the potential for earthquake vulnerability, both tectonic and volcanic. The tectonic hazard occurs because it is located between the active Flores Back Arc Thrust fault to the north and the Indonesian – Eurasian Ocean tectonic plate meeting fault (Santoso and Agustawijaya 2020). The potential for volcanic vulnerability comes from active volcanoes, Mount Tambora and Mount Sangeang. Bima Regency is on the island of Sumbawa, so it has an area prone to earthquakes. Figure 1 shows the number of earthquakes in 2011, 2014, and 2018 in eighteen sub-districts (BPS Kabupaten Bima 2020a). Of the eighteen sub-districts, only two have never experienced an earthquake in those years, namely Parado and Sape sub-districts. So almost all areas (89%) in Bima Regency are prone to earthquakes. In addition, 16 (sixteen) earthquake events from 2015 to 2017 with an earthquake magnitude of 5 - 6.2 occurred in this district (BMKG 2017).

The geological conditions and natural disasters that have often occurred in the past can affect the typology and construction of buildings (Lang et al. 2018). In addition, environmental factors also impact the vernacular house typology because physical and environmental elements are the basis for determining the position of the structure, orientation, choice of materials, layout, construction materials, and facade design (Erarslan 2019). From past earthquake events, buildings with wood-framed materials and construction have an excellent response to seismic in various parts of the world, including in Japan

Jepang (Okubo 2016; Horie and Kaneko 2017), Turkey (Aktaş 2017; Güçhan 2018; Erarslan 2019), Nepal (Paudel, Shima, and Fujii 2018), in the Indian Himalayan region (Chand, Kaushik, and Das 2019; 2020), Korea (Kim 2020), and Kaikoura in New Zealand (Buchanan and Moroder 2017).

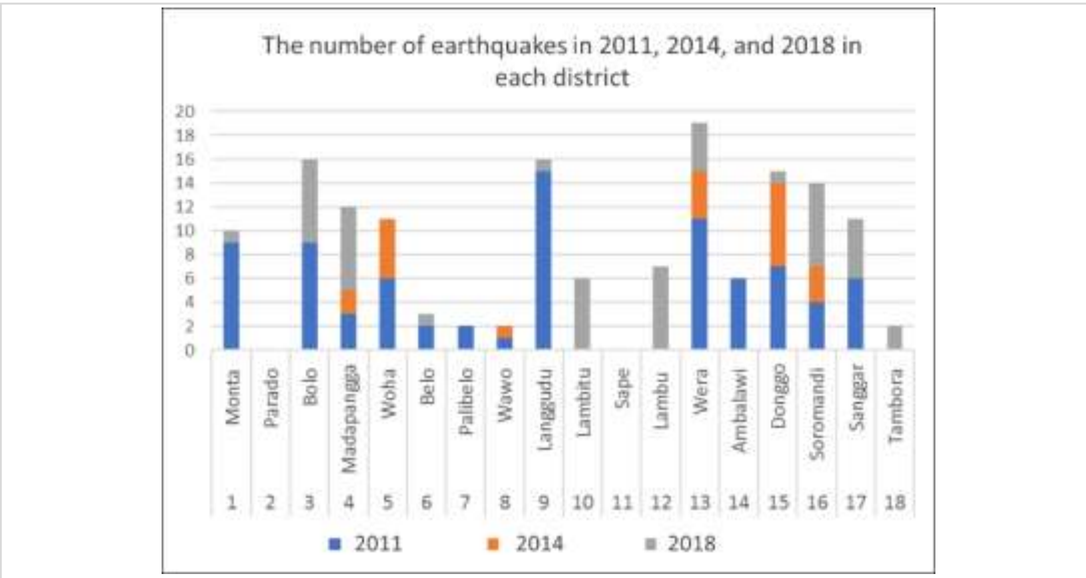

Figure 1. Number of earthquake events in 2011, 2014, and 2018 in each sub-district (BPS Kabupaten Bima 2020a)

The construction of vernacular stilt houses in earthquake-prone areas in Indonesia also uses timber materials. The performance of wood construction has been shown to have an adaptive response to earthquakes, such as omahada in Nias and uma lengge in Bima (Lumantarna and Pudjisuryadi 2012), ammu hawu on Sabu Island, NTT (Pranata and William 2013), Rurukan and Tonsealama vernacular houses in Minahasa (Sugeng Triyadi and Harapan 2011), and the Rejang vernacular house in Bengkulu (S. Triyadi, Sudradjat, and Harapan 2009). Therefore, wooden stilt houses in Bima Regency are significant for case studies related to structural and construction innovation to respond to earthquake-prone environmental conditions (figure 2).

Figure 2. *Uma panggu* in Bima Regency

Local seismic culture is the knowledge of local people about the effects of earthquakes in their area on buildings and how they consistently apply this knowledge to strengthen buildings (Ferrigni 2015b). Local people then pass on this knowledge to the next generation, and they make improvements. They carry out repairs or reinforcements as needed to anticipate the next earthquake. Local seismic culture has the following characteristics: using local materials, using local carpentry skills, and other local resources (Ortega, Vasconcelos, and Correia 2014; Ortega et al. 2017; Ortega, Vasconcelos, and Correia 2015; Ferrigni 2015b). In addition, these characteristics follow the local culture in the form of traditional techniques in vernacular buildings. The techniques include construction practices that are modest but effective in reducing the vulnerability of buildings to earthquakes (Ortega et al. 2017; Ortega, Vasconcelos, and Correia 2015). Traditional techniques that affect seismic performance in vernacular buildings include joints between structural elements, techniques for stabilizing structural elements and buildings, and techniques for resisting lateral loads (Ortega et al. 2018). Approaches to local seismic culture can be divided into three categories, namely rigidity, flexibility, and deformability (Ferrigni 2015a). Based on past studies, the local seismic culture in vernacular architecture in earthquake-prone areas in Indonesia is a more towards flexibility approach. It can be seen from the local timber used with dimensions that tend to be slender and the character of the connections between the rods and the supports, which provide opportunities for energy dissipation during an earthquake (Maer and Pudjisuryadi 2015; Prihatmaji, Kitamori, and Komatsu 2015; Manthani and Fauzan 2019; Sugeng Triyadi and Harapan 2011; Pranata and William 2013; Lumantarna and Pudjisuryadi 2012). Development in the context of local seismic culture also pays attention to building maintenance and strengthening to anticipate the next earthquake. Aspects of building activities in the context of local seismic culture have been carried out for generations by vernacular communities in earthquake-prone areas. So, the local seismic culture must be connected to the adaptability of vernacular architecture in earthquake-prone areas. Local seismic culture becomes part of vernacular community architectural practices in earthquake-prone areas. The seismic adaptability of vernacular architecture is closely related to local seismic culture.

The vernacular architecture's adaptability to environmental conditions refers to its ability to adapt to current conditions while considering the anticipation of future conditions. Earthquake-prone environmental conditions require the vernacular community in Bima Regency to adapt by carrying out 'innovations' in their houses' structural and construction systems. This study aims to identify the character differences in systems and types of wooden joints between elements and the construction of wooden stilt houses in Mbawa, Maria, Sambori, and Kole Village, Bima Regency, in the context of their seismic adaptability.

Method

This qualitative research uses a case study approach located in Bima Regency, which has an area of 4389.4 km² comprising 18 sub-districts (BPS Kabupaten Bima 2020b). A sampling process is needed to make it easier for researchers to determine locations and cases as research objects (Neuman 2014). The purposive sampling method was determined by considering the uniqueness of the location and ease of access to the location (Lucas 2016). Thus, the locations of field observation are in several villages in Bima Regency. The object that became the sample in this study was a vernacular house building in Bima Regency, a house on local wood stilts. From the sampling frame, the research locations were determined in four villages: Mbawa Village, Maria Village, Sambori Village, and Kole Village.

Field observations were carried out to obtain empirical data at the location of the research object. At this stage, researcher collected data through photo documentation, object measurements, and direct interviews with informants. The data includes photo documentation of research objects, sketches of the relationships between structural elements, and measured drawings. The research object was measured using manual and digital measuring instruments. The objects of observation were sixteen uma panggu, consisting of 6 (six), 9 (nine), 12 (twelve), and 16 (sixteen) posts. Interviews with building experts (*penggita*) and local traditional leaders were carried out to obtain data on the name and function of the space, the stages of construction, the names of building elements, their materials, and the practice of local people in repairing houses. Documentation, object measurement, and interviews with informants are complementary activities when collecting data in the field (Lucas 2016). After the data collection, the researcher analyzed the photo data, drawings, and fieldwork notes.

Analysis of case study qualitative research data can be carried out using several methods: identifying salient things (themes), identifying patterned regularities, connecting categories with the framework of literature studies, and displaying data findings in pictures, diagrams, and tables (Creswell 2013). Data analysis in this study was carried out in the following way:

A. Identify the salient parts of the structure and construction of each *uma panggu* and compare them between cases. Identification here includes analyzing the components in structural and construction parts to determine the type of joint.
B. Identify patterned regularity of the structure and construction of *uma panggu*.
C. Classify the data from the results of identifying the structure and construction of Uma Panggu into categories and link the categories with the results of a literature study.
D. Visualize data with pictures and diagrams to sharpen comparisons between cases in *uma panggu*.

Next, to find out the distribution of the types of relationships between components on the roof truss structure, the researchers conducted a descriptive statistical test, namely distribution analysis presented in a stacked column chart with a cumulative total for each column equaling 100%. This diagram was chosen because it can describe the percentage of the existence of each type of relationship between structural components in each *uma panggu case*.

Result and discussion

Uma panggu structural character

The stilt house in Bima Regency, called in the Bima language *uma panggu*, has a frame structure with a construction made from local wood. The structural frame consists of posts and beams. In several parts, namely the stilt structure and the roof truss structure, there are diagonal beams that function for stability and increase the rigidity of the structure. The structure and construction of the four types of *uma panggu* from four villages can be seen in figure 3. The lower structure consists of a stilted structure and a wall structure. The two subsections are categorized as substructures because the posts continue from the foundation to the roof truss. The posts function to hold the roof load. The upper structure is the roof structure.

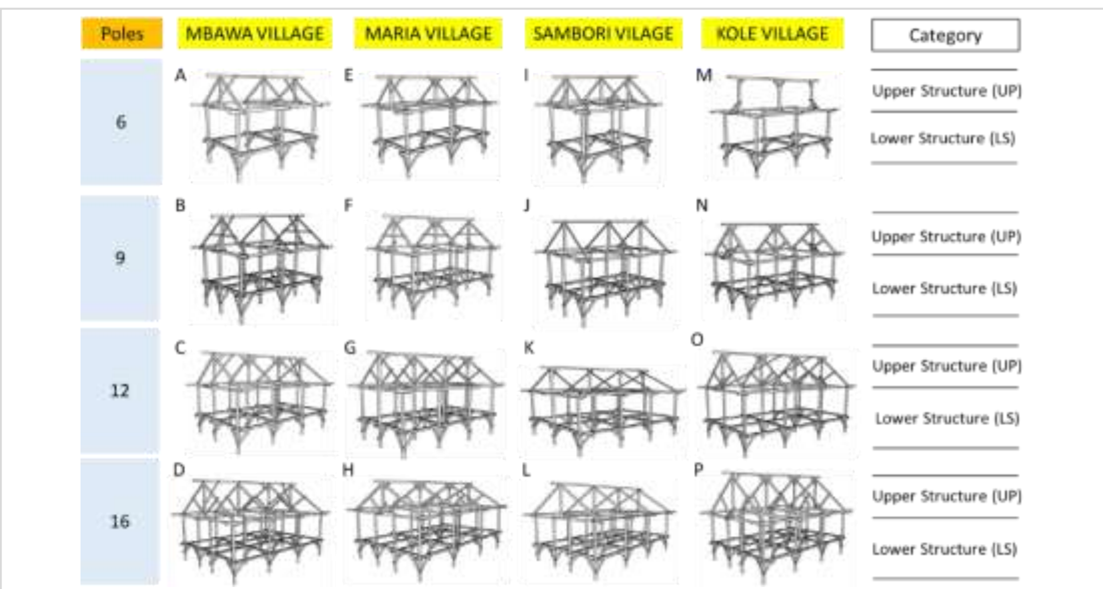

Figure 3. *Uma panggu* structure in 16 case studies

The structure and construction of the bottom are similar in each case. The structure consists of posts with walls and double beams arranged in a criss-cross, called *nggapi wela* and *nggapi doro*. The *tembuku* is part of the pole that protrudes like a mini corbel used to place long-sided double beams, namely *nggapi doro*. The short-sided double beam, namely the *nggapi wela*, is placed on the *nggapi doro*. The post legs are connected by double beams using diagonal beam called *ceko* to increase stability and stiffness against lateral loads. The elements of the posts with beams and posts with diagonal beams connected by wooden pegs called *wole*. The posts are placed on flat stones called *pali* as the foundation. Figure 4 shows the construction of the four elements in each case study.

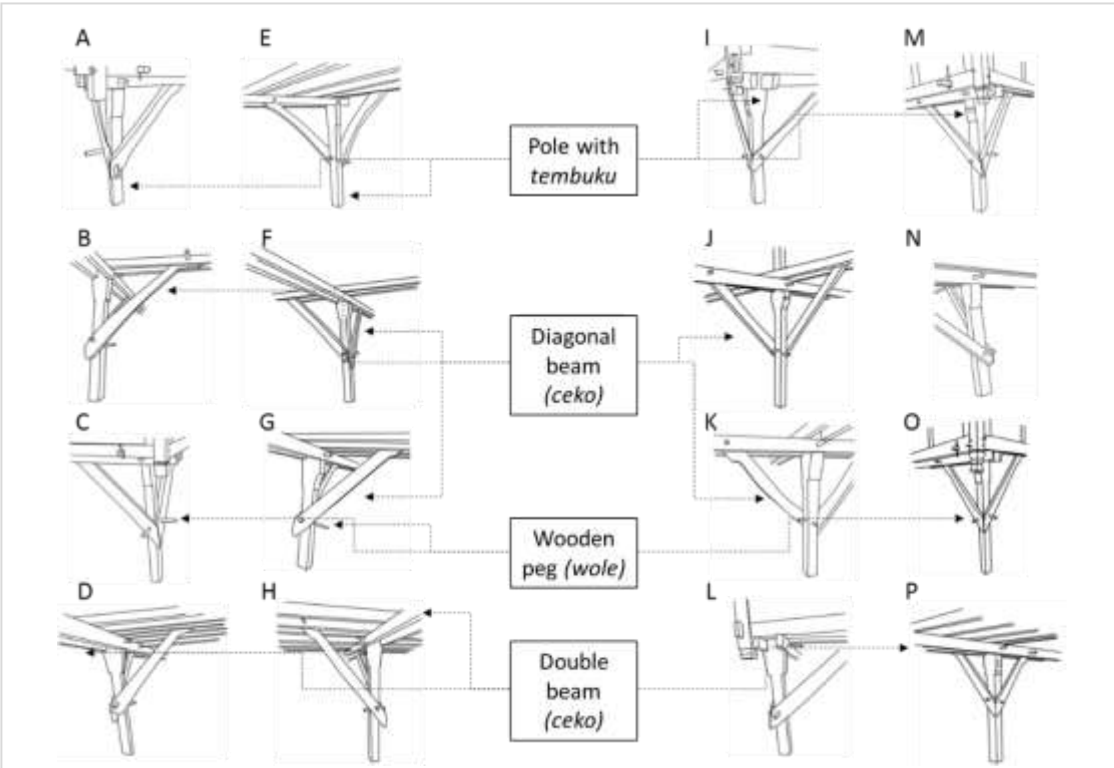

Figure 4. Construction of stilt structure of *uma panggu* in 16 case studies

The structural stability of the lower structure layout allows the uma panggu structure to withstand lateral loads during an earthquake. Mini corbel (*tembuku*) on posts and diagonal beams (*ceko*) became part of the innovations carried out by local builders called penggita. Both elements do not reduce the dimensions of the pile, so it does not affect the strength of the pile (Hariyanto, Triyadi, and Widyowijatnoko 2022). The connection between elements relies more on the contact area with the tembuku (indirect connection) and the dowel (direct connection). The combination of direct and indirect connection construction with pegs allows the structure to respond with an energy dissipation strategy during an earthquake (Crayssac et al. 2018; Ferrigni 2015b). The lower structure is stable and maintained by the community. An unpretentious technique that continues to be maintained because it has proven effective in its adaptability to earthquakes is part of the local seismic culture (Ortega, Vasconcelos, and Correia 2015; Ortega et al. 2017).

In contrast to the lower structure, which has the same construction in each case, the upper structure partially has a different construction, as shown in figure 3. The first difference lies in the roof frame on the transverse side (short span) front section. The second is in the long span; the difference lies in the structural frame and the placement of the diagonal rods on both sides. A more apparent difference in the short span can be seen in figure 5.

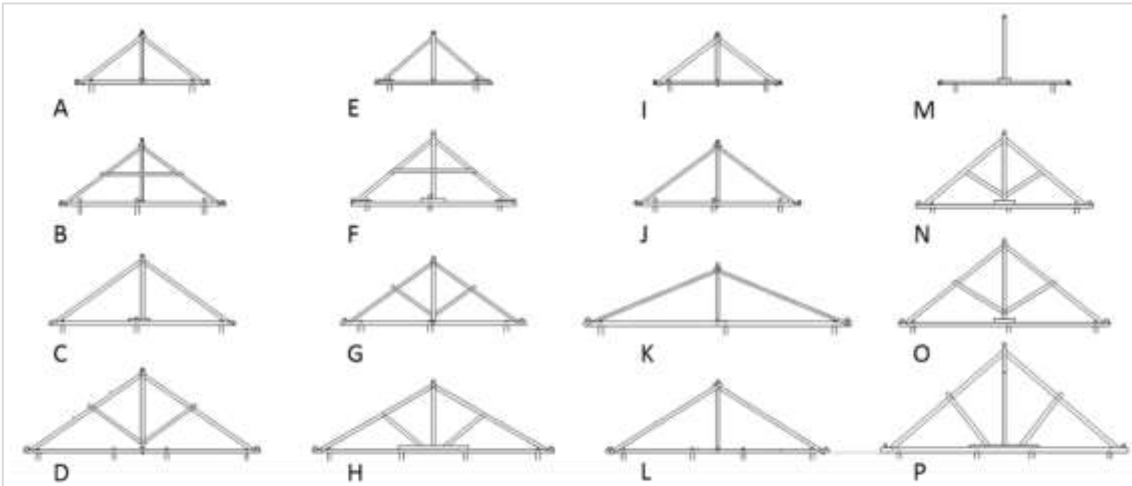

Figure 5. Cross section of the upper structure (roof frame) on the short span

Based on the structure form, the placement of diagonal members, and the type of joints, the sixteen cross-sections of the upper structure on the short span can be grouped into five types. The first type is represented by object B, object G represents the second type, the third type is represented by object J, the fourth type is represented by object M, and the fifth type is represented by object P. In terms of its frame system, object M has a different system than other types. The roof poles rest on beams without being given a diagonal beam element. So, the pile is more susceptible to lateral loads. The stability of this type relies on a rigid joint between the pillars and the supporting beam. The connection details for each object can be seen in figures 6, 7, and 8.

Upper structure components analysis

Each object is released into structural components to determine the types of the joint between components. The first analysis is done at the joint between the elements in the lower center (figure 6). The second is the joint between elements at the lower right end (figirue 7). The third part analysis is at the joint between the elements of the top center (figure 8).

Figure 6 shows the analysis of the upper structure component (US) in the first section. This section shows the relationship between the roof pole (bar 4/*panta*) and the transverse beams (bar 2/*pangere*), and the longitudinal beams (bar 3/*tonda pantabutu*) on the lower roof frame. The uniqueness of each type lies in the frame's form to respond to lateral loads and the details of the joints between structural members to respond to seismic. Stability for responding to lateral load in types 1, 4, and 5 relies on the existence of a diagonal bar (bar 5/*siku*).

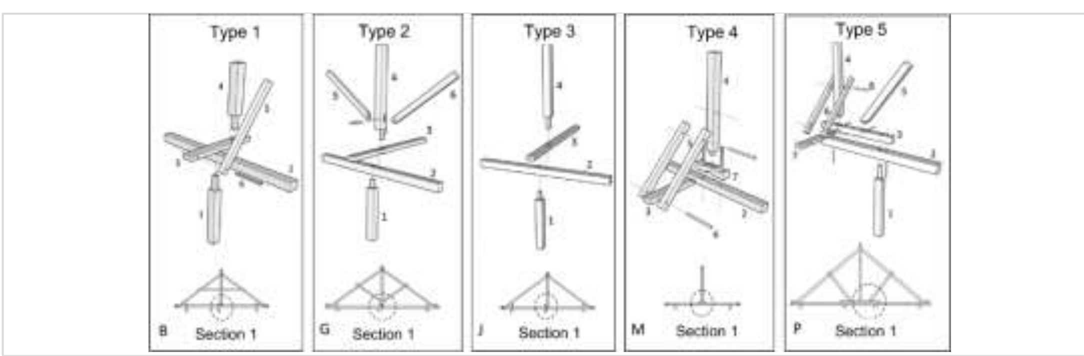

Figure 6. Analysis of upper structure components in section 1: object B (Hariyanto et al. 2020), objects G, J, M, and P

Figure 7 shows the analysis of the upper structure component (UP) in the second section. This section shows the relationship between the post (bar 1/*ri'i*) and the cross beam (bar 2/*pangere*) and the joint between bar 2 (*pangere*) and bar 3 (*panggalari wela*) at the end of the lower roof frame. In addition, types 1, 2, 3, and 5 describe the relationship between bars 2 (*pangere*) and 4 (*siku*). To respond to lateral loads in the direction of short spans, structures of type 1, 2, 3, and 5 rely on a rigid relationship between the post (bar 1/*ri'i*) and bar 2 *(pangere*) and between bar 2 (*pangere*) and bar 4 (*siku*). In type 4, the lateral load is responded to by a rigid joint between the post (bar 1/*ri'i*) and bar 2 (*pangere*).

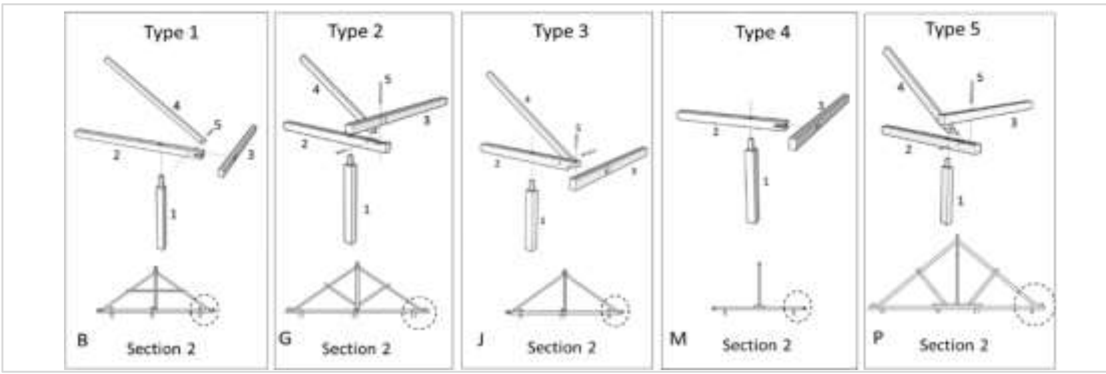

Figure 7. Analysis of upper structure components in section 2: object B (Hariyanto et al. 2020), objects G, J, M, and P

Figure 8 shows the analysis of the upper structure component (US) in the third section, the upper roof frame structure. First, this section shows the relationship between the post (bar 1 /*ri'i*) and the longitudinal beam in the Y direction (bar 2 /*kalibawo*) for all types. Second, the joint between bars 1 (*ri'i*) and 2 (*kalibawo*) and bars 3 and 4 (*siku*) in types 1, 2, 3, and 5. Third, the joint between components: bars 1 (*ri'i*) and 2 (*kalibawo*) with bar 5 (*siku*). Structures in types 1, 2, 3, and 5 rely on the stability elements of bars 3 and 4 (*siku*) to respond to lateral loads in the direction of short spans. Structural frames in types 1, 2, 4, and 5 use stability elements called diagonal beams for responding to lateral loads in the direction of long spans.

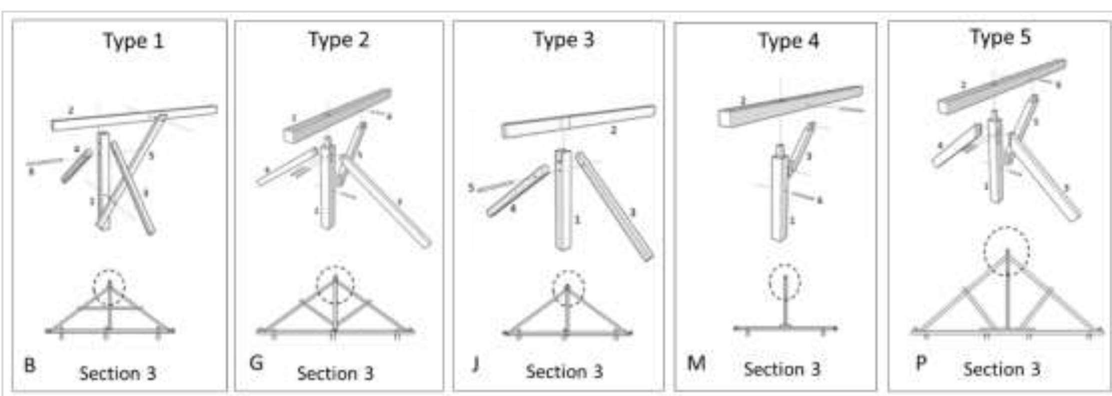

Figure 8. Analysis of upper structure components in section 3: object B (Hariyanto et al. 2020), objects G, J, M, and P

A stacked column diagram displays the identification results analysis from the decomposition between the structural components. The identification result of the first part can be seen in figure 9, the second part in figure 10, and the third part in figure 11.

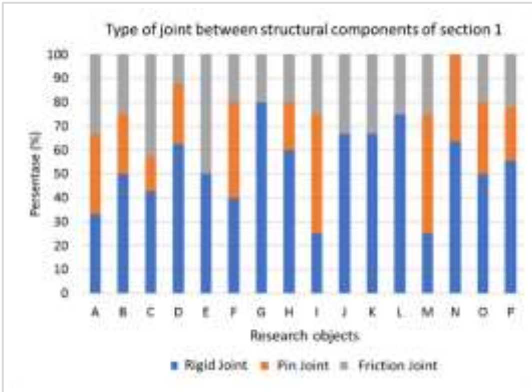

Figure 9. The percentage of rigid, pin, and friction joints in section 1 of the roof structure in each case

Figure 9 shows the percentage of rigid, pin, and friction joints in section 1 of the roof structure in each case (A – P). The distribution analysis results show three connection characters between components in that section: rigid–pin–friction, rigid–friction, and rigid–pin. Rigid joints were found in all cases, pin joints in eleven cases, and friction joints in fifteen cases. The existence of a wood construction technique that applies the nature of pin joints using pegs and friction joints can support the adaptability of the uma panggu roof structure in the context of its earthquake-prone environment.

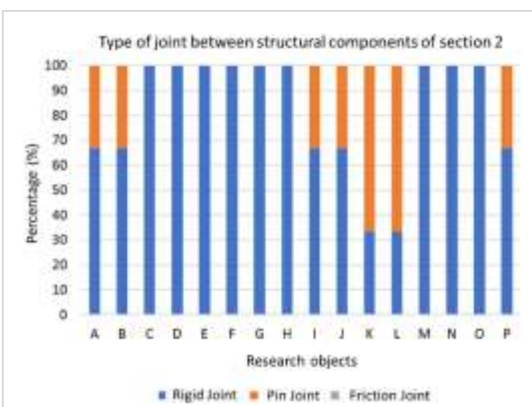

Figure 10. The percentage of rigid, pin, and friction joints in section 2 of the roof structure in each case

Figure 10 shows the results of identifying the types of joints between components in section 2 (two) in each case (A – P). From the distribution analysis results, 2 (two) characters of the joint between components in that section can be found: rigid – pins and rigid only. Rigid connections (rigid) are found in every object, and pin connections are found in objects A, B, I, J, K, L, and P. The existence of a wood construction technique that applies the properties of pin joints with a peg can support the adaptability of the Uma Panggu structure in the context of its earthquake-prone environment. Figure 11 shows rigid joints in 11 (eleven) cases, pin joints in 9 cases, and friction in 8 (eight) cases. Some cases only apply rigid joints in section 3 (three) of the roof structure, namely F, G, H, M, N, O, and P.

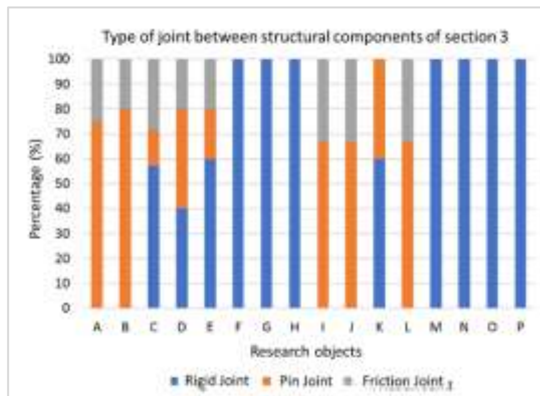

Figure 11. The percentage of rigid, pin, and friction joints in section 3 of the roof structure in each case

Rigid joints can increase the rigidity of the structural system, while pin and friction can increase the flexibility of the building structure. The integration of these two aspects: rigidity and flexibility, is needed to support the structure's performance against seismic loads. However, the dominance of the stiffness character in the relationship between components is found in the upper structure of section 2 (figure 10) and section 3 (figure 11) of the cases M, N, O, and P. It indicates that there is an effort by the community to strengthen the building structure. They might see the deformation of the upper structure as a weakness, not as part of adaptability.

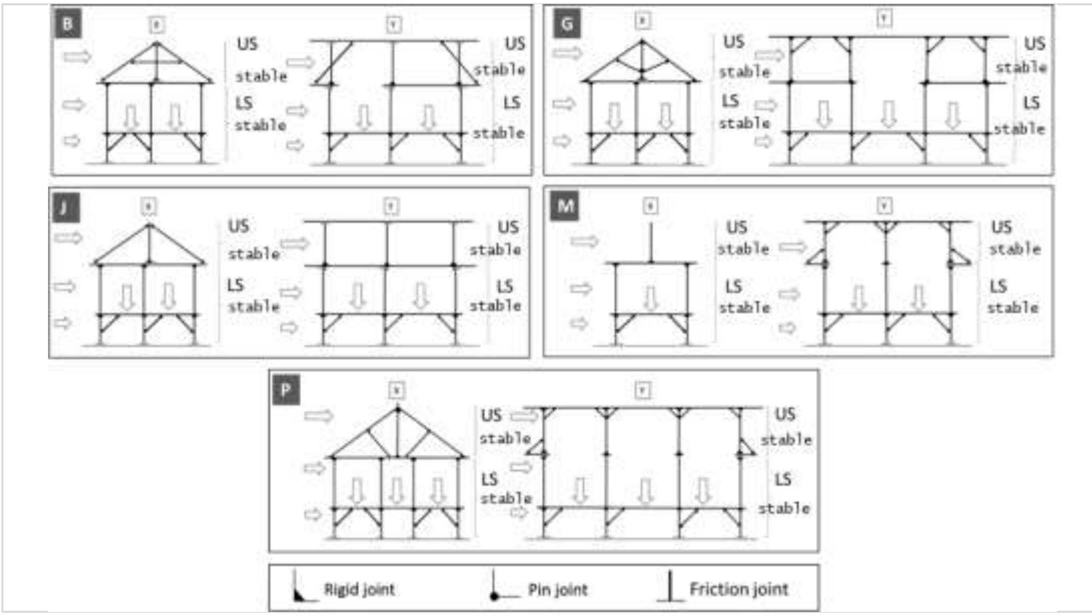

Figure 12. Structural system stability in case B (Hariyanto et al. 2020), case G, J, M, and P

Rigid, pin, dan friction joints on the lower and upper structural components are arranged in a vertical structure layout, as shown in figure 12. This layout not only fulfills the stability and rigidity criteria of the structure but also provides opportunities for movement during an earthquake. It happens because there are friction joints at specific components so that when an earthquake occurs, an energy dissipation mechanism can occur (Hariyanto, Triyadi, and Widyowijatnoko 2020; Lumantarna and Pudjisuryadi 2012; Maer and Pudjisuryadi 2015). This innovation can be found in the lower and upper structures of uma panggu. So, the structure of the uma panggu in Mbawa, Maria, Sambori, and Kole villages can be categorized in a frame system with rigid joints, pins, and friction. Rigid joints can receive axial forces and moments, whereas pin joints can only receive axial forces (Kemp 2004). Friction joints provide an opportunity to shift the structure during an earthquake, resulting in energy dissipation. The energy dissipation strategy is effective for slender frame structures such as the uma panggu in their earthquake adaptation. Integrating each component in the roof frame with construction innovations has proven to respond to its earthquake-prone environment. It is part of the innovations by local building experts in Bima.

Innovation of wood joints on the *uma panggu* Roof structure

Each structural component must be appropriately connected to transmit vertical and horizontal loads to the ground. In structures with wood materials, the form of joint construction varies greatly, but generally, the various forms can be categorized into pin and rigid joints. Rigid joints can receive axial forces and moments, whereas joint joints can only accept axial forces (Kemp 2004). Apart from having pin and rigid characteristics, the wooden joints in the uma panggu roof truss also have friction joints in some parts. One example is the friction joints on the uma panggu roof truss with 9 (nine) posts in Sambori Village (case J), as shown in figure 13. The application of friction joints by local builders is not without reason. When an earthquake occurs, the most significant deviation (maximum deflection) occurs at the top of the upper structure (Charleson 2008). However, what was designed by local builders in Bima does not refer to the maximum deviation theory. Local builders designed the structure and construction of uma panggu based on experience and the context of its earthquake-prone environment.

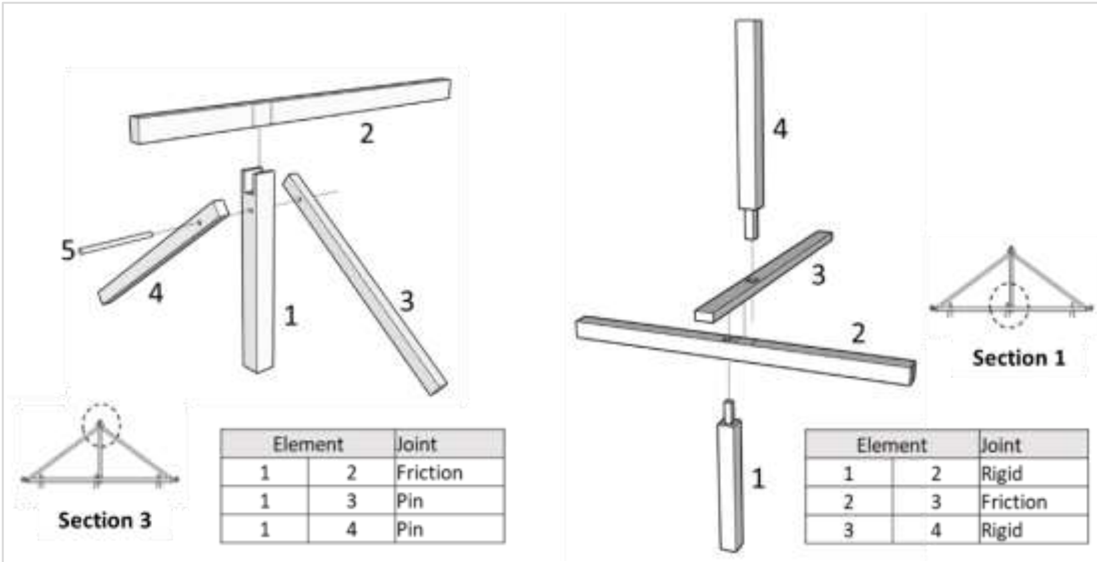

Figure 13. Friction joint on case J

Construction on vernacular building structures is an attempt by local builders to find appropriate and practical techniques to assemble structural materials to respond to gravity and lateral loads (Oliver 1997). This effort requires a long time because it involves a process of trial and error (Hărmănescu and Enache 2016). Wood joining techniques in vernacular building structures can be part of applying traditional techniques in local seismic cultures (Ortega et al. 2018). Connection techniques are applied to unite elements in a structure for load distribution in buildings. Local builders make wooden joint construction to protect the building during an earthquake. The connection between these components has a character that can be used as a seismic control strategy.

From the results of identifying the character of the wooden joints on the roof truss structure of the uma panggu, flexibility is the local seismic culture approach in wooden stilt houses in Bima. In addition to the wooden joint character, the use of local wood with dimensions that tend to be slender also strengthens this approach. With the flexibility approach, the building accommodates the movement of the structure during an earthquake. This movement provides opportunities for the dissipation of energy during an earthquake. This mechanism is part of the pattern of adaptability of the *uma panggu* roof structure to its earthquake-prone environment.

Conclusion

Researchers analyzed structural components and found three common characteristics: rigid, pin, and friction joint. A rigid joint can increase rigidity, while pin and friction joints can increase flexibility. The integration between the aspects of rigidity and flexibility supports the structure's performance against seismic loads. Lately, local people tend to upgrade rigidity to the upper structure. However, it can reduce the flexibility of the roof structure. The flexibility property of the structure is related to the energy dissipation strategy. Bima's vernacular architecture's local seismic culture leads to a flexible approach. However, in some cases, the dominance of the stiffness character is in the joint between the upper structure components. It shows that there are community efforts to strengthen the structure of the building. Local people may see flexibility as a weakness rather than as part of adaptability.

In addition, identifying the connection types between components in the upper structure of uma panggu can indicate that the local seismic culture in the vernacular architecture in Bima leads to flexibility approach. The frame structure of uma panggu with joint innovation allows energy dissipation during an earthquake. The construction of the structure uses local wood materials with dimensions that tend to be slender. The upper structure of uma panggu is more susceptible to deformation than the lower structure, indicating that the flexibility approach was 'deliberately' carried out by local construction experts to provide opportunities for energy release due to earthquakes.

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Agus Dwi Hariyanto contributed to the research concepts preparation, methodologies, investigations, data analysis, visualization, articles drafting and revisions.

Sugeng Triyadi contribute to the research concepts preparation and literature reviews, data analysis, of article drafts preparation and validation.

Andry Widyowijatnoko contribute to methodology, supervision, and validation.